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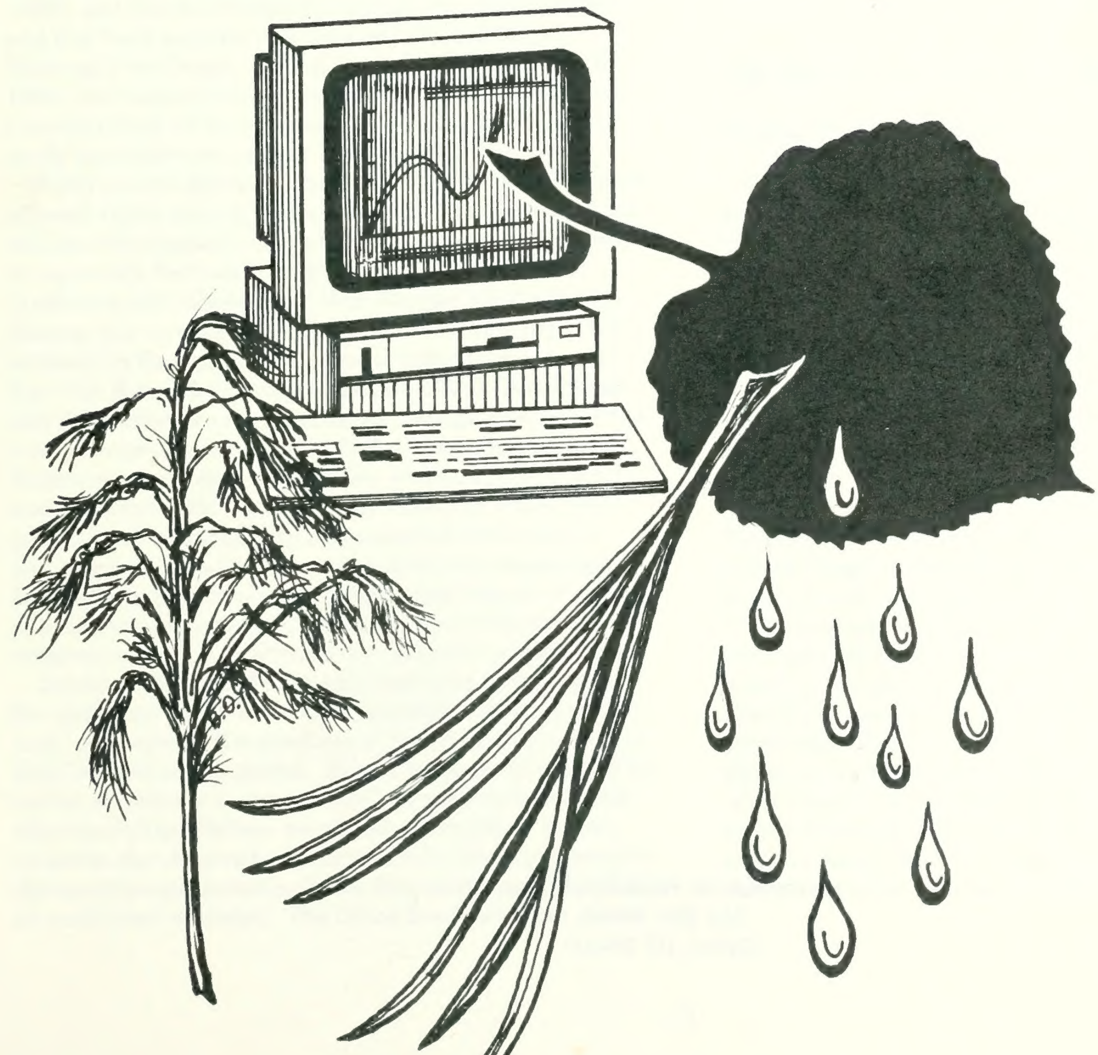
Predicting Equilibrium Moisture Content of Some Foliar Forest Litter in the Northern Rocky Mountains

Hal E. Anderson



THE AUTHOR

HAL E. ANDERSON has been team leader of the basic research section of the Fire Fundamentals research work unit since 1979. He joined the staff at Intermountain Station's Intermountain Fire Sciences Laboratory (formerly known as Northern Forest Fire Laboratory) in Missoula, MT, in 1961 and served as project leader of the fire physics project from 1966 to 1979. He previously worked with General Electric Company from 1952 to 1961 on thermal and nuclear instrumentation. He received his B.S. degree in physics from Central Washington University in 1952. Anderson retired in April 1990.

RESEARCH SUMMARY

Forest foliar litters that make up the fine fuels involved in spreading wildfires may vary in equilibrium moisture content, EMC, by 7 percent or more. This research reports the differences in EMC by species, the changes in EMC due to relative humidity and fuel temperature, and the predictions of EMC by applying a form of the Gibbs free energy equation. Results show that EMC's of only a few litter types are similar to the EMC of wood and that all litter types exhibited lower EMC's than wood at high temperatures and humidities. Test conditions ranged from 278 °K (40 °F) to 322 °K (120 °F) and from 10 to 90 percent RH.

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INTRODUCTION

The past half century has seen many attempts to quantify moisture content, MC, of wildland fuels and to incorporate these values into systems for predicting fuel flammability and potential fire behavior. Hardy (1983) describes the work of Harry T. Gisborne, who was studying fuels in the 1920's, and who eventually devised a fire danger meter that depended on the moisture content of wood dowels (Gisborne 1948).

Several studies have investigated moisture content to determine its influence on wildland fuel flammability: of wood (Simard 1968); of fine fuels such as hardwood leaves (Dunlap 1932); fine fuels in southern forests (Blackmarr 1971), Australian forests (King and Linton 1963), and forests of eastern Canada (Van Wagner 1972); and fine fuels entered into the early United States National Fire Danger Rating System, NFDRS (Keetch 1966). Air temperatures, near 23 °C (80 °F) and relative humidity from 20 to 90 percent have often been used to study fuel moisture content and flammability.

Study results generally indicated that moisture content of wood varies among tree species (Simard 1968) and that the moisture content of wood is usually lower than that of nonwoody fuels such as grass, needles, and leaves (Anderson and others 1978; Van Wagner 1972). Nevertheless, the current NFDRS (Cohen and Deeming 1985) is based on the moisture content of wood sticks, drawn from the Wood Handbook (USDA FS 1974). Adsorption and desorption are represented by a single curve over the entire range of humidity and fuel-surface temperatures. Moisture values drawn from such curves would typically under predict EMC for nonwoody fuels and would overpredict their flammability and potential fire behavior. The research reported here was initiated to determine EMC's of various nonwoody, foliar litter fuels over a range of temperatures and humidities and thus improve the accuracy of flammability and fire behavior predictions.

Determining an EMC for each fuel type that poses a fire potential would be an unreasonable and unnecessary task, particularly if a small set of fuel groups with similar EMC's could be calculated. Nelson's research (1983, 1984) on the sorption of water by cellulosic materials provides that capability. Nelson developed an empirical model, based on the observed exponential relationship between a thermodynamic variable, Gibbs free energy, and the EMC of a cellulosic material. The Gibbs free energy per gram of sorbed water is measured in terms of absolute temperature, degrees Kelvin, and relative humidity, RH. Nelson (1983, 1984) noted that earlier researchers had reported the change in Gibbs free energy as a function of moisture content, MC, for cellulosic materials (Babbitt 1942; Kelsey and Clarke 1956; Stamm and Loughborough 1935). In addition, Anderson and McCarthy (1963) had reported an exponential variation for the differential heat of wetting as a function of moisture content.

While illustrating the possible formation of foliar litter groups in terms of EMC's, the research described here also provides another test of the applicability of Nelson's equation to materials with less cellulose content than wood. Woody materials have cellulose contents near 75 percent, while conifer needles have contents near 40 percent (Susott 1980; Susott and others 1975).

METHODS AND MATERIALS

Field Procedures

Foliar litters consisting of grasses, deciduous leaves, and conifer needles were collected in western Montana and northern Idaho for study. One sampling was done in the fall after the current-year leaf and needle cast, collecting only the recently cast dead foliar litter. Another sampling was done in the late spring collecting just the weathered foliar litter. The general areas of sampling are shown in figure 1, with the following specific collections: western white pine (*Pinus monticola* Dougl.) at the Priest River Experimental Forest in northern Idaho; lodgepole pine (*Pinus contorta* Dougl.) and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), in the headwater drainages of Fish Creek in Montana; Engelmann spruce (*Picea engelmannii* Parry), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), western redcedar (*Thuja plicata* Donn.), and grand fir (*Abies grandis* [Dougl.] Lindl.), in the general area of the Powell Ranger District in Idaho. Litter samples collected in the vicinity of Missoula, MT, were ponderosa pine (*Pinus ponderosa* Laws.), quaking aspen (*Populus tremuloides* Michx.), western larch (*Larix occidentalis* Nutt.), and cheatgrass (*Bromus tectorum* L.). The fuels were brought to the Intermountain Fire Sciences Laboratory in Missoula, MT, where they were mechanically sorted, cleaned without washing, and placed in cool, dry storage until the testing was done.

Figure 1—General locations of sampling for the foliar litter studies.

Laboratory Procedures

Three temperature-controlled cabinets were used to condition litter samples. Two cabinets were used to establish high and low MC starting points, and the third one maintained a constant atmospheric humidity. The high-humidity condition was established over water at the test temperature in the first cabinet and the low-humidity condition of 2 to 3.5 percent relative humidity (RH) was set in the second cabinet, with ambient air heated to 322 °K (120 °F). This procedure was similar to Van Wagner's (1972) and provided comparability. Although the possibility of a decrease in hygroscopicity existed because of influences like internal and external physical stresses, the results indicated that this was not a major influence. Within each cabinet, RH was monitored with the aid of a dew point detector. Samples of a selected litter were weighed, placed in cabinets 1 and 2, weighed periodically until the weight change had stabilized, and then placed in cabinet 3 so the EMC was approached with desorbing and adsorping litter samples. Again, samples were weighed periodically until the weight change had stabilized. This period of time was from 1 to 2 weeks, depending on the foliar litter being tested. When the samples had reached their final values, they were processed with xylene distillation to determine the final MC. Saturated salt solutions were used to maintain the relative humidity at each of the test temperatures used. Table 1 shows the humidities achieved at the various temperatures.

An initial test series was done at 295 °K (71 °F) with litter samples considered to be recently cast. The results indicated the samples were often a mixture of recently cast and weathered materials. A second series was tested at 300 °K (80 °F) using litter samples collected more carefully. Four of these fine fuels, ponderosa pine and Douglas-fir needles, cheatgrass, and quaking aspen leaves, were also tested at 278 °K (40 °F) and 322 °K (120 °F) to investigate the change in EMC with temperature. Fuel and air temperatures were the same in these tests, and two or more replications were done for each sample at each temperature and relative humidity.

Results from these tests were organized by litter type, recently cast or weathered condition, adsorption or desorption, and the temperature-humidity combinations.

Data Analysis

In addition to studying the differences in EMC values for the various foliar litter fuels, a method of estimating EMC at different temperatures and humidities was investigated. The most promising approach was the Gibbs free

Table 1—These saturated salt solutions maintained the relative humidities shown for the test temperatures

Salt	Temp	RH	Temp	RH	Temp	RH	Temp	RH
	°K	*Pct*	*°K*	*Pct*	*°K*	*Pct*	*°K*	*Pct*
Li Cl	278	17	295	13.5	300	11.8	322	12.7
$MgCl_2$	278	—	295	34.0	300	30.0	322	—
$Mg(NO_3)_2$	278	61	295	53.0	300	53.0	322	48.0
NaCl	278	—	295	74.0	300	70.5	322	—
KNO_3	278	82	295	85.0	300	78.0	322	88.0
°C	5		22		27		49	
°F	41		72		80		120	

energy exponential relationship presented by Nelson (1983). The decrease in Gibbs free energy per gram of sorbed water is described by (Nelson 1983, 1984; Skaar 1972):

$$\Delta G = -(RT/M)\ln(\mathrm{RH}/100), \text{ cal/g} \qquad (1)$$

where R is the universal gas constant, 1.9872 cal °K/mole; T is the absolute temperature, (°C + 273 = °K); M is the molecular weight of water, 18.0153 g/mole; and RH is the relative humidity in percent. Limits on ΔG were set by considering the values as RH approaches zero and 100 percent. When the RH goes to zero, ΔG would become negatively infinite but is limited to a value that is defined when the RH has reached a small but finite value of 0.66 percent. Therefore ΔG_0 represents the Gibbs free energy change possible at very dry conditions:

$$\Delta G = \Delta G_0 \text{ when MC} = 0. \qquad (2)$$

ΔG_0 is determined from a plot of $\ln(\Delta G)$ versus MC and extrapolating to MC = 0.

When the RH approaches 100 percent, the MC approaches fiber saturation moisture content, MC_s, and the Gibbs free energy goes toward zero so:

$$\Delta G = 0 \text{ when MC} = MC_s). \qquad (3)$$

Nelson (1983, 1984) found a simpler logarithmic model to have better linearity with $\ln(\Delta G_0) = 0$ (or $\Delta G = 0$) when MC equals MC_s:

$$\ln(\Delta G) = \ln(\Delta G_0)\,(1 - MC/MC_s). \qquad (4)$$

To be as accurate as possible, equation 4 was modified by defining MC_υ as the moisture content value when $\ln(\Delta G) = 0$ and is only an approximation of fiber saturation moisture content, MC_s under conditions of desorption. For adsorption, MC_υ approximates the product of MC_s and the hysteresis ratio (the average ratio of adsorption to desorption moisture contents). Equation 4 then becomes:

$$\ln(\Delta G_0) = \ln(\Delta G_0)\,(1 - (MC/MC_\upsilon)) \qquad (5)$$

and may be applied to adsorption and desorption EMC data.

This equation can be modified to a form suitable for testing experimental data by least squares regression analysis when $A = \ln\Delta G_0)$ and $B = -(A/MC_\upsilon)$:

$$\ln(\Delta G) = A + B(\mathrm{MC}). \qquad (6)$$

Values for ΔG were determined by equation 1 for each temperature and relative humidity tested. The ΔG values were combined with the observed EMC values to develop the data sets used to determine the coefficients A and B. Six to ten observations of EMC were used in each combination (table 2). Analysis showed that MC was a predictor of $\ln(\Delta G)$ for species, temperature, and RH. Within the range of temperatures tested, I developed a quadratic or linear equation to predict A and B for a given, °K, temperature. The form of the equations for predicting A or B is:

$$A = C_n + C_{n+1}(\mathrm{TEMP}) + C_{n+2}(\mathrm{TEMP}^2) \qquad (7)$$

where

TEMP = fuel surface temperature, °K

C_n, C_{n+1}, and C_{n+2} = constants of regression.

With a given temperature and RH, we could then determine $\ln(\Delta G)$, $\ln(\Delta G_0) = A$ and $MC_\upsilon = -(A/B)$ and estimate MC using:

$$MC = MC_\upsilon\,(1 - (\ln(\Delta G)/\ln(\Delta G_0)). \qquad (8)$$

This provided the means to evaluate the variability in EMC of foliar litter fuels, check for similar groups of litter, define how both the sorption process and the state of weathering influence EMC, and show how the EMC's of foliar litter relate to the wood fine fuel EMC used in the NFDRS. The EMC's of the forest foliage litter fuels are presented in the accompanying figures and referenced to the EMC of wood at the same temperature. Curves for wood were generated by regression equations produced in the same way as for foliar litter but using the EMC data in table 3-4 of the Wood Handbook (USDA FS 1974).

RESULTS

All the tests showed a typical sigmoid-shaped curve for EMC as a function of RH when EMC is assumed to approach zero as RH nears zero (fig. 2). Nearly all the foliar litter samples showed higher EMC's than calculated by the method used for wood sticks in the NFDRS. Recently cast Douglas-fir needles showed a sorption change in EMC at 300 °K (80 °F) very similar to that of wood used in the NFDRS (fig. 2). At the same conditions, western larch needles showed the highest EMC's (fig. 2). The other litter samples tested have data located between these two and show that the EMC's can differ by 2 to 6 percent, depending on the litter samples. The weathered samples showed similar responses, but are shifted toward higher EMC's and have less hysteresis among the foliar litter samples (fig. 3). The adsorption and desorption curves in figures 2 and 3 show the hysteresis loop to be 2 percent or less EMC for RH from 10 to 90 percent and a temperature of 300 °K (80 °F).

The EMC's at 278 °K (40 °F) and 300 °K (80 °F) were higher than those of wood, but at 322 °K (120 °F) a significant decrease in EMC occurred (fig. 4). This decrease is more pronounced than reported for wood in the Wood Handbook (USDA FS 1974) and as used in the NFDRS. At 278 °K (40 °F), moisture contents of the foliar litter samples could be 4 percent higher at low RH and as much as 7 percent higher at high RH. As the temperature increases, the EMC decreases until at 322 °K (120 °F) all four litter samples have EMC's lower than wood at RH's above 40 percent. Cheatgrass had a small change in EMC, 4.2 to 10.6 percent, as RH went from 12.7 to 88 percent at 322 °K (120 °F) (fig. 4). Ponderosa pine needles' EMC predicted values from equations 6, 7, and 8 show the decrease in EMC at 10, 30, and 70 percent RH as the temperature increases (fig. 5).

Table 2—Coefficents for the regression equation of Gibbs free energy equation, $\ln(\Delta G) = \ln(\Delta G_o)\ (1-(MC/MC_v) = A+B(MC)$ where $A = \ln(\Delta G_o)$ and $B = -\ln(\Delta G_o)/MC_v$. AD = adsorption and DE = desorption

Species	Condition	Sorp	Intercept A	Slope B	Max. EMC MC_v	R^2	No.	MSE
			278 °K					
Cheatgrass, CG	Recent	AD	4.7661	–15.42	0.3091	0.9972	8	0.0552
		DE	5.3671	–16.82	.3191	.9599	8	.2087
	Weathered	AD	4.9450	–16.72	.2957	.9879	8	.1146
		DE	5.4090	–17.69	.3058	.9672	8	.1889
Douglas-fir, DF	Recent	AD	4.4922	–17.71	.2536	.9856	8	.1250
		DE	5.2952	–14.36	.3688	.8995	8	.3304
	Weathered	AD	4.8490	–17.02	.2849	.9992	8	.0290
		DE	5.5010	–17.99	.3059	.9872	8	.1177
Ponderosa pine, PP	Recent	AD	4.7654	–17.05	.2796	.9968	8	.0586
		DE	5.7350	–20.57	.2789	.9791	8	.1508
	Weathered	AD	4.8478	–16.47	.2944	.9954	8	.0709
		DE	5.5151	–18.20	.3030	.9835	8	.1339
Quaking aspen, QA	Recent	AD	4.5277	–12.32	.3676	.9594	8	.2101
		DE	5.3474	–14.80	.3612	.9788	8	.1517
	Weathered	AD	4.7716	–12.82	.3722	.9906	8	.1010
		DE	5.6836	–17.01	.3341	.9995	8	.0238
			295 °K					
Cheatgrass, CG	Recent	AD	4.9145	–18.15	0.2566	0.9290	8	0.3068
		DE	5.1989	–18.49	.2812	.9604	10	.2291
Douglas-fir, DF	Recent	AD	4.7141	–17.08	.2760	.9784	10	.1465
		DE	4.7377	–13.99	.3386	.9594	10	.2007
Engelmann spruce, ES	Recent	AD	4.5901	–16.69	.2751	.9643	10	.1881
		DE	4.3865	–10.68	.4108	.9393	10	.2453
Grand fir, GF	Recent	AD	4.7842	–15.84	.3020	.9830	10	.1362
		DE	4.4185	–11.05	.3998	.8933	10	.3418
Lodgepole pine, LP	Recent	AD	4.7646	–18.26	.2610	.9910	10	.1094
		DE	5.1764	–18.10	.2859	.9886	10	.1231
Ninebark, NB	Recent	AD	4.7501	–13.53	.3498	.9176	10	.3028
		DE	5.0120	–15.05	.3330	.9046	10	.3258
Ponderosa pine, PP	Recent	AD	5.0017	–20.09	.2489	.9905	10	.1122
		DE	5.1240	–17.84	.2873	.9849	10	.1417
Quaking aspen, QA	Recent	AD	5.2308	–18.78	.2785	.9901	10	.0989
		DE	5.0881	–15.12	.3365	.9444	10	.2349
Subalpine fir, SF	Recent	AD	4.9898	–21.48	.2324	.9960	10	.0732
		DE	4.8060	–15.93	.3016	.9708	10	.1968
Western white pine, WP	Recent	AD	5.1260	–17.34	.2957	.9879	10	.1152
		DE	5.1667	–13.95	.3703	.9948	10	.0755
Western redcedar, WC	Recent	AD	4.9899	–17.61	.2834	.9894	10	.1086
		DE	4.7710	–13.01	.3667	.9422	10	.2536
			300 °K					
Douglas-fir, DF	Recent	AD	4.6768	–18.92	0.2471	0.9871	10	0.0100
		DE	4.7713	–17.55	.2719	.9650	10	.0271
	Weathered	AD	5.2789	–20.98	.2516	.9823	10	.0137
		DE	5.2840	–18.90	.2795	.9961	10	.0030
Engelmann spruce, ES	Recent	AD	4.4698	–15.44	.2896	.9647	10	.0274
		DE	4.5928	–15.49	.2964	.9489	10	.0396
	Weathered	AD	4.8936	–17.43	.2808	.9996	10	.0003
		DE	5.1382	–16.74	.3070	.9992	10	.0006
Grand fir, GF	Recent	AD	4.6475	–16.42	.2829	.9837	10	.0126
		DE	4.8952	–18.11	.2703	.9811	10	.0147
	Weathered	AD	5.1336	–16.78	.3060	.9979	10	.0017
		DE	5.4385	–16.74	.3249	.9939	10	.0047
Lodgepole pine, LP	Recent	AD	4.7601	–17.80	.2674	.9908	10	.0071
		DE	5.1552	–18.62	.2768	.9877	10	.0096
	Weathered	AD	5.0319	–17.12	.2939	.9935	10	.0050
		DE	5.3049	–16.84	.3150	.9951	10	.0038
Western larch, WL	Recent	AD	4.8922	–14.99	.3264	.9714	10	.0222
		DE	5.1903	–15.61	.3326	.9658	10	.0265
	Weathered	AD	5.1161	–16.68	.3068	.9926	10	.0057
		DE	5.6226	–18.48	.3043	.9899	10	.0078

(con.)

Table 2 (Con.)

Species	Condition	Sorp	Intercept A	Slope B	Max. EMC MC_v	R^2	No.	MSE
			300 °K (Con.)					
Ponderosa pine, PP	Recent	AD	4.9588	−18.32	.2706	.9868	10	.0102
		DE	5.3411	−19.71	.2710	.9965	10	.0027
	Weathered	AD	5.1275	−19.46	.2634	.9949	10	.0039
		DE	5.4581	−19.51	.2798	.9954	10	.0036
Quaking aspen, QA	Recent	AD	4.9747	−15.75	.3159	.9783	10	.0168
		DE	5.3707	−17.70	.3035	.9642	10	.0277
	Weathered	AD	5.1099	−15.93	.3209	.9933	10	.0052
		DE	5.3934	−15.49	.3481	.9470	10	.0411
Subalpine fir, SF	Recent	AD	4.6962	−18.25	.2573	.9881	10	.0092
		DE	4.8972	−19.13	.2560	.9732	10	.0208
	Weathered	AD	5.0260	−18.67	.2692	.9947	10	.0041
		DE	5.3391	−19.00	.2810	.9948	10	.0040
Western white pine, WP	Recent	AD	5.0038	−17.44	.2870	.9981	10	.0015
		DE	5.2969	−17.32	.3058	.9934	10	.0051
	Weathered	AD	5.1133	−15.91	.3213	.9981	10	.0015
		DE	5.4419	−16.50	.3298	.9977	10	.0018
Western redcedar, WC	Recent	AD	4.7442	−16.90	.2807	.9838	10	.0126
		DE	4.9530	−17.14	.2890	.9801	10	.0154
	Weathered	AD	5.0398	−15.84	.3181	.9973	10	.0021
		DE	5.2021	−14.44	.3602	.9982	10	.0014
			322 °K					
Cheatgrass, CG	Recent	AD	5.4364	−37.38	0.1454	0.9721	6	0.2348
		DE	6.0096	−42.67	.1408	.9947	6	.1022
	Weathered	AD	5.4710	−42.00	.1302	.9338	6	.3617
		DE	6.0549	−52.69	.1149	.9346	6	.3594
Douglas-fir, DF	Recent	AD	4.7339	−23.57	.2008	.9773	6	.2112
		DE	4.8620	−25.77	.1886	.9835	6	.1803
	Weathered	AD	5.6470	−34.95	.1616	.9949	6	.0999
		DE	5.9220	−35.74	.1657	.9958	6	.0914
Ponderosa pine, PP	Recent	AD	5.4363	−32.12	.1692	.9959	6	.0904
		DE	5.4314	−30.13	.1803	.9998	6	.0174
	Weathered	AD	5.8920	−36.90	.1597	.9811	6	.1933
		DE	5.9276	−34.52	.1717	.9943	6	.1065
Quaking aspen, QA	Recent	AD	6.0343	−39.17	.1540	.9937	6	.1117
		DE	6.4355	−40.90	.1573	.9840	6	.1780
	Weathered	AD	6.2567	−39.48	.1585	.9884	6	.1513
		DE	6.7023	−40.37	.1660	.9995	6	.0322

Although the EMC changes converge at low EMC's, the high temperature data have higher intercepts than the other temperatures, and low temperature data tend to have lower intercepts. This is indicated in figure 6, which shows how the $\ln(\Delta G)$ changes with EMC. The species were grouped visually and statistical tests were carried out at the 5 percent significance level to see if the regression lines in a proposed group were parallel and coincident. In a few cases, species could be grouped, but the results were not uniform. No consistent groupings were found for the recent cast or weathered conditions. The reason appears to be that the mean square errors, MSE, are so small that slight variations make significant changes in the computed F values. Instead of grouping by statistical methods, overlays were used to see if grouping by litter types was possible. Inspection indicated the best resolution of the litter types was obtained using ±2 percent EMC bands to group the foliar litter types. At 300 °K (80 °F) and both sorption processes the following groups could be separated in order of increasing EMC:

Recently Cast Litter

Group 1: Cheatgrass
Group 2: Douglas-fir, Engelmann spruce, grand fir, and subalpine fir
Group 3: Ponderosa pine, lodgepole pine, and western redcedar
Group 4: Quaking aspen, western larch, and western white pine

Weathered Litter

Group 1: Cheatgrass
Group 2: Douglas-fir, Engelmann spruce, and subalpine fir
Group 3: Ponderosa pine, grand fir, lodgepole pine, and western redcedar
Group 4: Quaking aspen, western larch, and western white pine

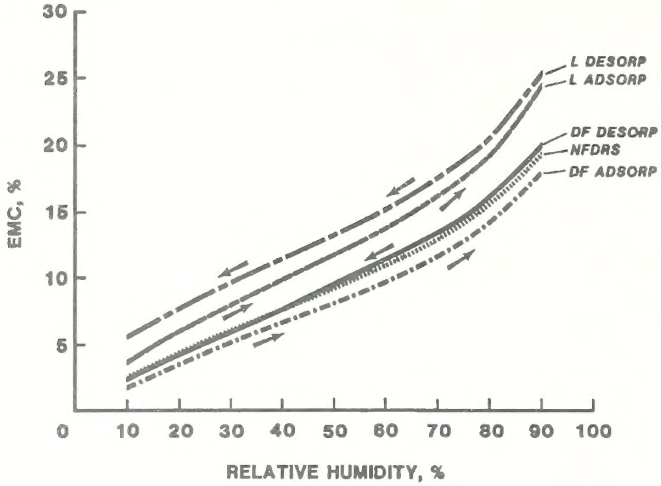

Figure 2—EMC curves of recently cast Douglas-fir needles and larch needles, plotted from Gibbs free energy equations at 300 °K for relative humidity, are compared to EMC values observed for adsorption, desorption, and NFDRS estimates.

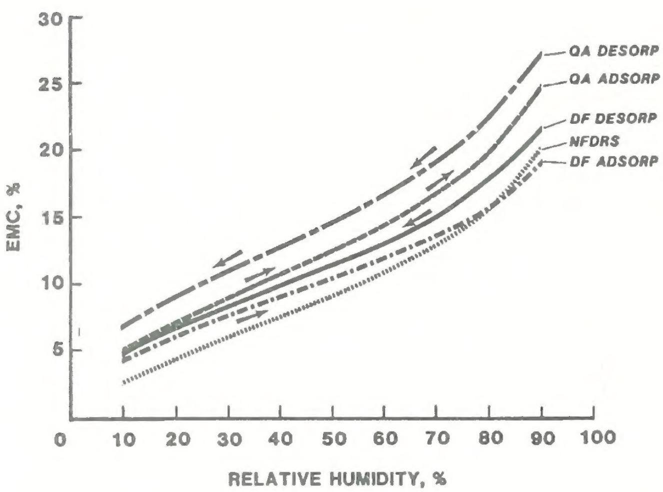

Figure 3—EMC curves of weathered Douglas-fir needles and weathered quaking aspen leaves, plotted from Gibbs free energy equations at 300 °K for relative humidity, are compared to EMC values observed for adsorption, desorption, and NFDRS estimates.

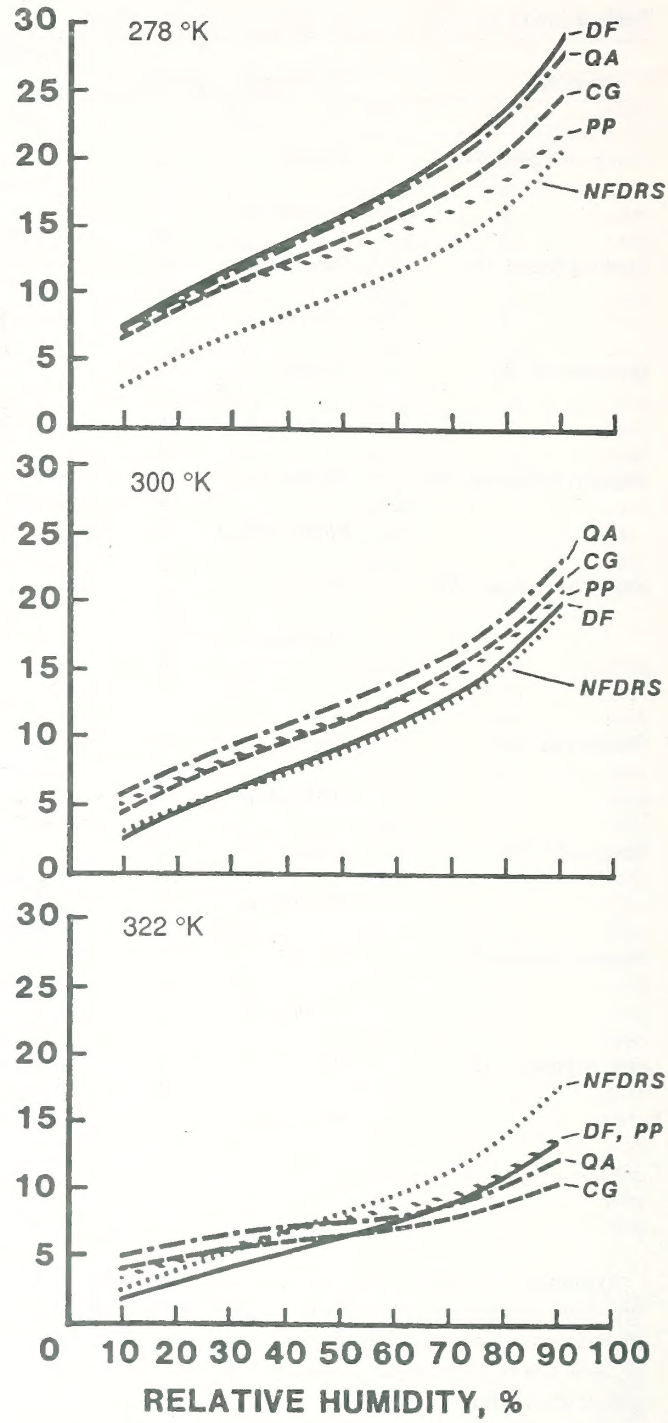

Figure 4—Changes in EMC desorption with temperature and humidity for aspen, cheatgrass, ponderosa pine, and Douglas-fir litter, compared to NFDRS estimates.

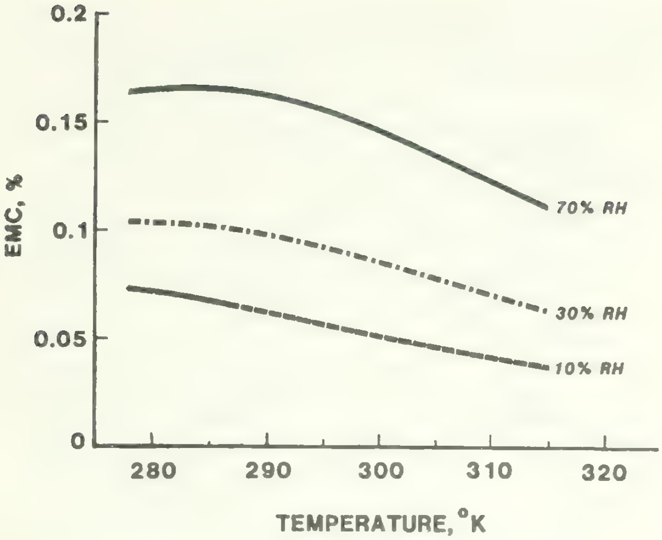

Figure 5—Decreases in recent ponderosa pine needles EMC desorption values at humidities of 10, 30, and 70 percent as surface temperatures increase are predicted and plotted from equations 6, 7, and 8.

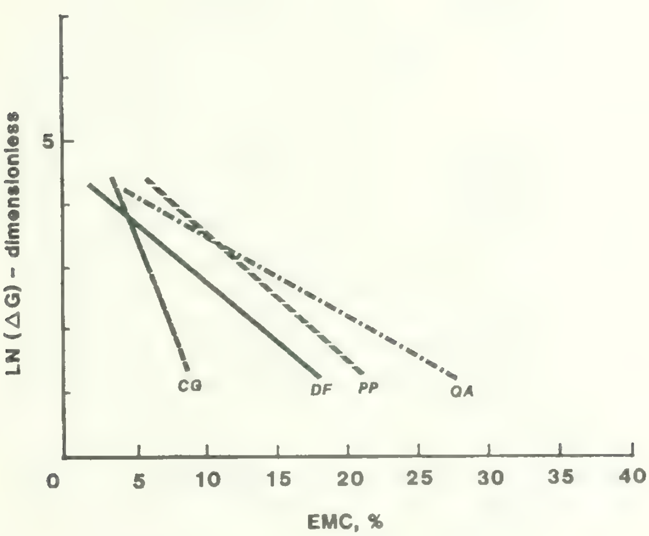

Figure 6—Variations in Gibbs free energy relationship for several litter fuels and conditions: Douglas-fir at 300 °K, recently cast in adsorption; ponderosa pine at 300 °K, recently cast in desorption; quaking aspen at 278 °K, weathered in adsorption; cheatgrass at 322 °K, weathered in desorption.

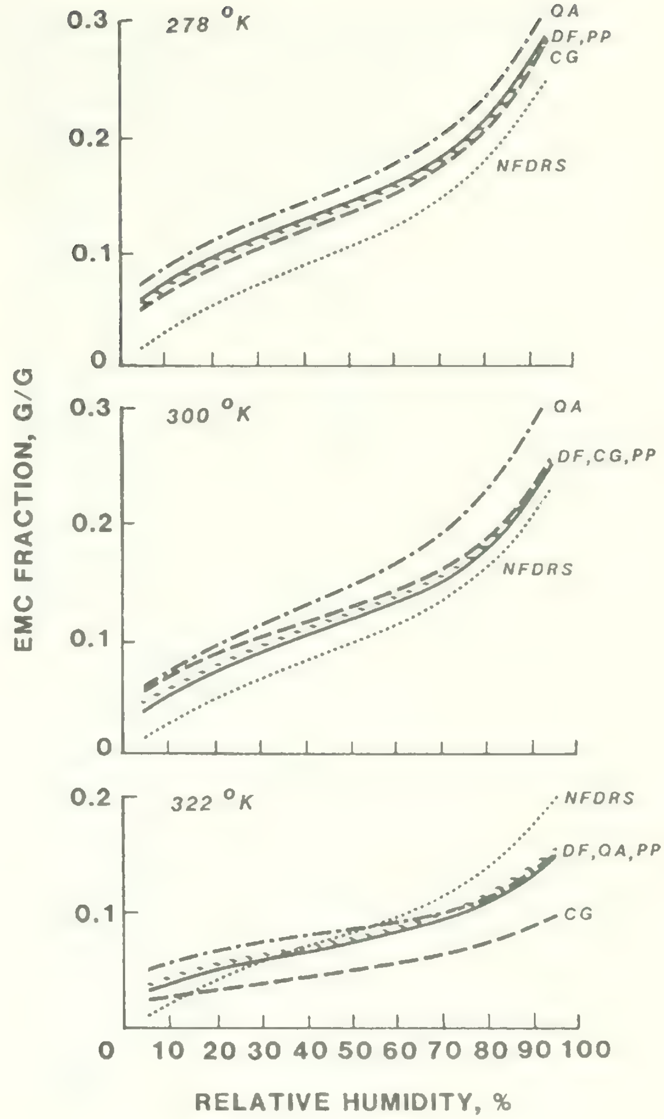

Figure 7—Desorption EMC's of weathered Douglas-fir, ponderosa pine, quaking aspen, and cheatgrass litter compared to wood used in NFDRS estimates. Data from weathered material shows more similarity than data from recently cast material.

Figure 7 illustrates the curves generated from equation 8 and the separation for the litter groups at 278, 300, 322 °K, desorption, and weathered conditions. A general grouping of foliar litter species was seen in the firs and spruce needle EMC data. Pine needle EMC's for recently cast or weathered conditions tended to group.

Coefficients for the Gibbs free energy equation, A and B, were found to be functions of temperature (figs. 4, 7). Data were analyzed at 278, 300, and 322 °K for ponderosa pine needles, quaking aspen leaves, and Douglas-fir needles. For cheatgrass, EMC data taken at 295 °K were used because those at 300 °K were not available. It was found that both A and B could be estimated by quadratic equations where the litter temperature was the independent variable. For cheatgrass, a linear regression provided a better fit for the A coefficient for all conditions except the recently cast material in desorption. This was also true for the Douglas-fir weathered material in adsorption. Each of the litter groups delineated above can be evaluated for expected EMC's by using equation 7 with C_1, C_2, and C_3 values given in table 3 to determine A and C_4, C_5, and C_6 values to determine B and then using equations 6 and 8 to calculate the expected EMC. The coefficients C_1 and C_4, C_2 and C_5, and C_3 and C_6 are given in table 3

Table 3—Coefficients for regression equations to predict A and B as functions of surface temperature for use in the Gibbs free energy equation, $\ln(\Delta G) = A + B(MC_v)$. $A = C_1 + C_2(TEMP) + C_3(TEMP^2)$, $B = C_4 + C_5(TEMP) + C_6(TEMP^2)$, R^2 = coefficient of variation squared, No. = number of observations

	Species			
	Douglas-fir	Ponderosa pine	Quaking aspen	Cheatgrass
		Recently Cast—Adsorption		
C_1	–9.309	26.300	52.639	.414
C_2	.08784	–.15758	–.35223	.01554
C_3	–.0001373	.0002883	.0006445	—
R^2	.98	.98	.99	.94
No.	34	34	34	24
C_4	–295.915	–1,081.460	–1,709.360	–972.061
C_5	1.98014	7.43318	11.90591	6.84375
C_6	–.0035232	–.0129658	–.0208685	–.0122398
R^2	.99	.98	.99	.99
No.	34	34	34	24
		Recently Cast—Desorption		
C_1	64.898	51.842	95.503	81.765
C_2	–.39084	–.30298	–.62584	–.52473
C_3	.0006348	.0004933	.0010847	.0008991
R^2	.99	.99	.97	.93
No.	34	34	34	24
C_4	–409.989	–1,000.250	–1,741.360	–1,471.690
C_5	2.87550	6.75430	12.08836	10.26116
C_6	–.0052246	–.0116198	–.0211430	–.0180860
R^2	.99	.99	.99	.99
No.	34	34	34	24
		Weathered—Adsorption		
C_1	–.154	43.563	70.514	1.566
C_2	.01809	–.28016	–.46990	.01216
C_3	—	.0005069	.0008397	—
R^2	.90	.97	.99	.99
No.	24	24	24	14
C_4	–780.621	–1,234.710	–1,742.930	–1,733.460
C_5	5.47058	8.57029	12.12182	12.00537
C_6	–.0097980	–.0150654	–.0212174	–.0209711
R^2	.99	.99	.99	.99
No.	24	24	24	14
		Weathered—Desorption		
C_1	82.609	52.480	141.973	1.219
C_2	–.52508	–.32254	–.93345	.01497
C_3	.0008912	.0005528	.0015943	—
R^2	.96	.91	.98	.88
No.	24	24	24	14
C_4	–1,389.800	–1,193.320	–2,281.030	–2,611.640
C_5	9.54490	8.19501	15.63398	18.08085
C_6	–.0165845	–.0142747	–.0269426	–.0314763
R^2	.99	.99	.99	.99
No.	24	24	24	14

and must be carried out to 3, 5, and 7 decimal places, respectively, for the A and B coefficients to be accurate. Rounding up EMC values imposes a bias so the values are always offset from the observations.

The EMC values over a range of litter temperatures can be estimated from the equations given in tables 2 and 3 developed for the four litter types tested. It appears that these results can be extended to the litter groups by using the equations for the representative litter type because the litter samples could be grouped within ±2 percent of each other. Litter group 1 (recently cast, adsorption and desorption) is represented by the cheatgrass EMC's. Litter group 2 (recently cast, adsorption and desorption) is represented by the Douglas-fir EMC's, while litter group 3 is represented by the ponderosa pine EMC's and litter group 4 by the quaking aspen EMC's. The weathered samples, with adsorption and desorption phases, group in a similar manner but most of the conifers needle types group with the Douglas-fir and ponderosa pine needle data. Groups 2 and 3 could be grouped as one because the calculated EMC's are generally within ±2 percent of each other.

DISCUSSION

The possibility of organizing the various foliar litters into litter groups is encouraging because it suggests that only a few such groups of litters or fuels are needed to describe the general change in EMC. Use of this information does require the user to make observations of the field situation and decide what species are present and whether the foliar litter is weathered or recently cast. Although the EMC data for recently cast litters are useful for a short period of each year, the weathered EMC data will probably be useful throughout the year. Weathering results in the EMC shifting to higher values. The available literature was reviewed for data that could be compared to see if the results are consistent with other measurements. Information published by King and Linton (1963), Blackmarr (1971), and Van Wagner (1972) was used to determine if the EMC's of other fuels could be estimated using regression equations determined in this work. Results were compared to those reported by Nelson (1984) and good agreement was found. In addition, the EMC equations to calculate wood moisture in the NFDRS were checked.

Litter group 1, cheatgrass (recently cast, adsorption and desorption), matched Blackmarr's EMC's for wiregrass (*Aristida stricta* Michx.) and broomsedge (*Bromus secalinus* L.), staying within 2 percent at all the tested RH's. Van Wagner's (1972) EMC data for a grass (*Calamagrostis* sp.) was consistently 2 percent higher. The tussock grass (*Poa caespitosa*) EMC's reported by King and Linton were lower than that for cheatgrass by more than 2 percent and had a different rate of change to RH. The desorption EMC's curve for cheatgrass were 1.5 to 2.0 percent higher than the EMC curve presented for wood.

Litter group 2, fir and spruce needles (recently cast, or weathered, adsorption and desorption), appeared to be unique in that no other needles for these or similar species have been tested. This group's EMC values were found to fit best the eucalypts (*E. obliqu* L'Herit. and *E. radiata* Sieb. ex DC.) leaf data of King and Linton (1963). The EMC's of the eucalpyts stayed within 2 percent of litter group 2 EMC's to an RH of 70 percent, where the eucalyptus litter exhibited higher EMC's. These litters may group because of the extractives, crude fats, or cutin they contain. At 300 °K the litter group 2 EMC's for recently cast, desorption conditions matched the EMC's for wood.

Litter group 3, pines and cedar (recently cast, adsorption and desorption), EMC's behaved similiarly at low RH's with red pine (*P. resinosa* Ait.) from Van Wagner (1972) and radiata pine (*P. radiata*) from King and Linton (1963). At 82 percent RH, however, radiata pine had a 9 percent higher EMC during adsorption. Although none of the litter samples used for comparisons were identified as weathered, five pine species were found to match best with litter group 3 (weathered, adsorption and desorption): eastern white pine, (*P. strobus* L.) and jack pine (*P. banksiana* Lamb.) from Van Wagner (1972); loblolly pine (*P. taeda* L.), slash pine (*P. elliottii* Engelm.), and longleaf pine (*P. palustris* Mill.) from Blackmarr (1971). For this litter group, the match in EMC was always within 2 percent until the RH increased to 80 percent or more. Most of the weathered litter samples corresponding to the litter samples of the recently cast litter groups 2 and 3 merge into the weathered phase of litter group 2.

Litter group 4, quaking aspen, western larch, and western white pine (recently cast, adsorption and desorption), compared well with sugar maple (*Acer saccharum* Marsh.) and trembling aspen (*Populus tremuloides* Michx.) from Van Wagner (1972) up to a RH of 78 percent, where the latter went to higher EMC's. Generally, the EMC's were within 1 percent at RH's below 78 percent. The deciduous leaves used by Blackmarr, southern red oak (*Quercus falcata* Michx.), post oak (*Q. stellata* Wangenh.), and mockernut hickory (*Carya tomentosa* Nutt.), compared best with the litter group 4 (weathered, adsorption and desorption) EMC's. The adsorption values at midrange RH for the oaks were about 2 percent lower in EMC than those found in this study.

The use of EMC's for the litter groups discussed here, rather than those for wood, to represent foliar litter would produce some significant changes in estimating fire danger or fire behavior. For instance, all of the litter groups' EMC's are within 1 percent of each other at 278 °K (40 °F) and 10 percent RH, but are 3.5 to 4.5 percent higher than those for wood. At 300 °K (80 °F) and RH's from 10 to 90 percent, pine needles are about 2 percent higher in EMC than wood and fir needles. Deciduous leaves are about 3.5 percent higher than wood over the same RH range. This means that for a system based on the EMC of wood, the fire danger or fire behavior in needle and leaf fuels can be overestimated. But the reverse can happen at higher temperatures, such as the 322-°K (120-°F) test temperature, where all of the EMC's for foliar litters become less than that for wood above 40 percent RH, with cheatgrass being lower by nearly 7 percent. In these cases, the litter may be ignitable sooner than expected or continue to burn even though the RH shows an increase.

SUMMARY

EMC values for some foliar litter, fine forest fuels, such as Douglas-fir needles, were close to that of the NFDRS values for wood for different temperatures and humidities. EMC's of most litter samples, however, are higher than those of wood. For recently cast, adsorption and desorption, these litters can be classified from lowest to highest EMC's into four general groups: grasses, spruce and fir needles, pine and cedar needles, and aspen and larch foliage. At 300 °K (80 °F) the spruce, fir, and ponderosa pine needles had the lowest EMC's even after having weathered over winter for 6 months. The rest of the weathered litter groups are, in order from lowest to highest EMC's, the pines; the grasses, and then larch, aspen, and cedar.

The EMC's can be estimated by equations that relate the change in moisture content to temperature and humidity. This approach uses the relationships given in the Gibbs free energy equations. The estimates are within ±2 percent MC of the observed values for temperatures of 278 to 322 °K and RH's of 10 to 90 percent. Litter EMC's deviate from the EMC for wood enough that separate calculations for fire danger rating or fire behavior estimates may be required. These equations provide a means for estimating EMC and MC that allows resolution of the differences that exist in fuel types.

Temperature had a significant effect on EMC. Foliar litters' EMC's were much lower at high temperatures than wood. This may explain the increased flammability of some fuels on hot days or when heated by direct sunlight so the fuel temperature is higher than the air temperature.

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Forest foliage that comprises much of the forest floor litter has higher equilibrium moisture content, EMC, than woody components. The EMC's at 300 °K were found to increase as follows: grasses < fir-spruce needles < pine-cedar needles < aspen leaves-larch needles. Equations that express Gibbs free energy associated with moisture content were used to develop regression equations that predict the EMC's from temperature and relative humidity, RH, for temperatures between 278 °K (40 °F) and 322 °K (120 °F) and RH's between 10 and 90 percent.

KEYWORDS: fuel moisture, fire behavior, flammability, fuels, wildland fire

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